1-G Human Factors for Optimal Processing and Operability of Constellation Ground Systems

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Abstract—In the early stages of the Exploration Systems Mission Directorate (ESMD), during the transition from the Orbital Space Plane Project (OSP) Program to the Constellation Program, the requirements for 1-G (Earth gravity) human factors were not well-defined. [12]Since that time, the requirements have been defined at different levels of maturity for Flight Hardware/Software, Ground Support Systems (GSS) and Ground Support Equipment (GSE). Effectively all areas are leveraging human factors for optimizing ground processing of Flight Hardware. This paper gives an overview of these areas; within the outer-mold-line of the Flight Hardware, at the Ground Systems to Flight Systems interface, and the design of the GSS and GSE leading up to the Flight Systems Interface. The major focus of this paper is on the current requirements and processes for infusing human factors into the designs of GSS and GSE. This paper aims to explain to the human factors practitioner how human factors were infused into a large program with an existing culture that does not have human factors listed separately in the work breakdown structure (WBS). This paper also aims to educate the Constellation Program (CxP) about the importance of human factors in ground processing and launch operations of launch vehicles.

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1 978-1-4244-2622-5/09/$25.00 ©2009 IEEE
2 IEEEAC paper#1286, Version 1, Updated 2008:12:18

1. Introduction

The major focus of this paper is on the steps taken to develop the current requirements and processes for infusing human factors into the design of Ground Support Systems (GSS) and Ground Support Equipment (GSE) as dictated by the Constellation Program (CxP) Ground Operations Project (GOP) at Kennedy Space Center (KSC).

Aspects that helped promote an emphasis on GSE and GSS were: (1) the CxP previously accepted ground assembly and maintenance human factors requirements for designing flight hardware, (2) the relative lack of human factors considerations with respect to ground processing during the design phase of the Space Transportation System (STS), i.e., the Space Shuttle, (3) dedicated people, (4) leveraging past lessons learned from other Programs, (5) focusing on what can be done and how to achieve this to add value to the stakeholders, (6) building on successes as the CxP Program evolved.

The significance of this paper is that there has not been such an emphasis on ground processing human factors requirements across a program in the Kennedy Space Center during NASA's 50 year history.

2. Brief history of KSC Human Factors prior to CxP and Ground Operations Project

Orbital Space Plane Project (OSP)

Prior to the OSP, there were other NASA plans for future human space flight, such as the 2nd Generation Shuttle. During the evolution of these projects there was an ongoing effort to infuse human factors requirements into these designs. These efforts were driven by lessons learned from Space Shuttle operations at KSC. Because there was a lack of emphasis on operability with the Space Shuttle design, in the late 1980's a team of industrial and human factors engineering experts was established to improve the hardware and to examine the processes already in place. By the end of the 1990's, many areas were analyzed which led to useful lessons learned that could be used to promote process improvements for future ground processing at KSC.

OSP System Design Review

Although there were many lessons learned in Space Shuttle processing there was still a lack of emphasis on infusing human factors in the WBS for new projects. For example, although a position for human factors was created within the OSP organization at KSC, this position came late in the formulation phase of the Program. The main emphasis was working with the Flight Crew human factors group at JSC, with little authority to impact ground processing hardware designs. At the System Definition Review (SDR), there was little evidence of human factors considerations in ground processing designs. [2] Stambolian This was due in part to a lack of well-defined human factors requirements for ground processing during the Systems Requirements Review (SRR) phase. But as the OSP project progressed, KSC voiced concerns for the need for ground processing human factors to the external stakeholder human factor team at Johnson Space Center (JSC).

From the internal stakeholder aspect, because KSC had never proactively incorporated human factors design on a project or program, it was not clear where human factors requirements should reside in the OSP documentation. Other successful human factors programs and documentation (e.g., Federal Aviation Administration (FAA) Human Factors Design Standards (HFDS) 001, Johnson Space Center (JSC) Man-Systems Integration Standards NASA STD 3000) were used as a guide, but the OSP organization at KSC did not have the same culture and extensive use of human factors as did the FAA or JSC, thus the OSP human factors approach was different and OSP documents only received comments where it seemed appropriate. At the end of OSP there were lessons learned which showed the need for greater emphasis on human factors. [1]Foley

3. THE BEGINNING OF CXP

Human factors requirements for Crew Exploration Vehicle (CEV)

As Exploration Systems was established, the role for ground processing human factors again was not clear. There was an effort to gather lessons learned and several white papers were submitted for all areas including 1-G human factors. [3] Stambolian Fortunately, as Exploration progressed, KSC's office supporting Exploration was given the opportunity to add ground maintenance human factors requirements into NASA-STD-3000 VIII (i.e., a draft human factors requirements document for CEV). To do this KSC went through MIL-STD-1472 (Department of Defense Design Criteria Standard, Human Engineering) and extracted the requirements that best fit the needs for ground processing and maintenance.

GOP Human Integration Engineering Plan

Around the same time, a Human Integration Engineering Plan (HEIP) for GOP was proposed but was not accepted, due mainly to the lack of direction from the Program. Although the HEIP was not formally approved, the overall plan of establishing human factors integration for the GOP continued.

Human factors requirements for all CxP flight hardware

As the Constellation Program progressed the decision was made to have ground processing human factors requirements for all flight vehicles (crewed and un-crewed). Since there were already ground human factors requirements in the draft NASA-STD-3000 VIII, leadership from NASA Headquarters (HQ)/ Marshall Space Flight Center (MSFC) and KSC decided to incorporate and improve these NASA-STD-3000 VIII requirements to include assembly and maintenance of all flight elements and put them into the Level-2 (L2) Human Systems Interface Requirements Document (HSIR). [4] Dischinger Now designers would not only plan for the maintenance of the crewed vehicle, i.e., the CEV, but also the assembly of an integrated launch vehicle, i.e., Ares-I. The development of the HSIR was a CxP L2 effort which was not a GOP responsibility, but with the inclusion of the assembly and maintenance section the HSIR resulted in great benefits for ground processing and improved human operability during assembly and maintenance of flight hardware. This effort was accomplished by writing Review Item Dispositions (RIDs), lobbying for these human factors requirements, and ongoing management support.

At this point the design of flight hardware was accounted for by the L2 HSIR. But it was unclear how human factors at the interface between the ground and flight hardware would be handled. Also within the GOP, the Level-3 (L3) Ground Systems Requirements Document (GS-SRD) was developed but did not contain any specific human factors requirements. Thus the next set of efforts was to account for the human factors at the Ground System to flight hardware interface through the L2 Interface Requirements Documents (IRDs), and to account for the GOP human factors requirements for GSE and GSS.

Ultimately the requirements in the IRDs were accepted and at that point human factors was being used to improve assembly and maintenance operations within the flight hardware and at the flight to ground hardware interfaces. The development of the human factors processes and requirements for the ground activities that lead up to the interface were left to the discretion of the L3 GOP since there were no L2 human factors requirements imposed on the GOP for GSE and GSS. Having L2 GSE and GSS human factors requirements for the GOP may have improved the acceptance of L3 human factors requirements.

4. KSC GOP HUMAN FACTORS

The following paragraphs explain the path taken to develop the ground human factors requirements and human factors assessment processes.

The first set of L3 ground human factors requirements

Because L2 documentation did not have specific human factors requirements to flow into the L3 GS-SRD, the GOP took the responsibility to add a set of human factors requirements into the GS-SRD. These requirements were intended to cover the key areas of launch processing concerns and were high level requirements, such as requirements for reach, envelope volume, visual access, damage prevention, lifting, and tool clearances. Since the HSIR requirements were developed by using the MIL-STD-1472 and with human factors experts at Johnson Space Center, Marshall Space Flight Center, Kennedy Space Center, and Ames Research Center, the baseline for developing these GS-SRD human factors requirements came from the same set of flight hardware ground assembly and maintenance design requirements for flight hardware in the L2 HSIR.

First ground human factors requirements document

During the SRR, there were Review Item Dispositions (RIDs) on the GS-SRD that required associated measurement data along with the human factors requirements. Because it would be difficult to add all this measurement data into the L3 GS-SRD, and because the human factors requirements set was mostly duplicated across the nine elements (Vehicle Integration Element (VIE), Moble Launch Element (MLE), Launch Pad Element (LPE), Spacecraft Processing Element (SPE), etc.) it was decided to remove the requirements from the GS-SRD and put a single set into a new document, the GS-HFRD. This document's main objective was to establish a set of high-level parent requirements focused on KSC's key human factors concerns, and lay out the scope of the different human factors requirements documents affecting the GOP such as HSIR, the Ground Systems (GS) to flight hardware IRDs, NASA-STD-5005, (Standard for the Design and Fabrication of Ground Support Equipment) and KSC-DE-512 (Facility, System, And Equipment General Design Requirements). The GS-HFRD, not baselined at this time, was intended to capture human factors areas of concern for the GOP.

Design Workshops

After preliminary development of the GS-HFRD, there was an opportunity to pilot test the GS-HFRD set of requirements through human factors engineering design workshops. [5] Kanki 9 designs near the 30% level were evaluated. This process was effective identifying the major human factors concerns for these designs. In addition, human factors stories of past operator experiences were collected, documented, and used to verify or improve the key human factors requirements in the GS-HFRD.

Ground human factors requirements aligning with previous KSC practices

Although the workshops were successful and the requirements in the GS-HFRD were accepted during the GS-SRD SRR, prior to base-lining the GS-HFRD there were concerns that the requirements would be difficult to verify.

Previous KSC human factors practices did not include hard requirements; instead human factor issues were sometimes addressed at the 90 % design reviews, where some human factors were addressed to improve the design. The practice in the past was to use the D&C Standards (Design and Construction Standards) process for verification which is more flexible in how the requirements are met, i.e., verifications are determined by the design engineers, and there is less stringent tracking and documentation of individual requirements in MIL-STD-1472. Thus a compromise was necessary to ensure that incorporating the ground systems human factors requirements would not be overly burdensome to the GOP. So it was decided that the verification method would be left up to the L5 design engineer and the L3 GS-SRD verification is only by inspection of the L5 documentation. This decision effectively reduced the intended authority of the GS-HFRD to other human factors standards such as MIL-STD-1472.

Because MIL-STD-1472 was already called out in NASA-STD-5005 and in the KSC-DE-512-SM to establish the human factor criteria for GSE and GSS, there was a concern that having both the GS-HFRD and the MIL-STD-1472 would cause confusion for designers. There were also concerns that if the GS-SRD took precedence it may not cover all the areas that are covered in the MIL-STD-1472.

Ground human factors requirements comparison to MIL-STD-1472

A comparison between the GS-HFRD and the MIL-STD-1472 was made. This comparison determined that the top level requirements in the GS-HFRD captured over 30% of the requirements in the MIL-STD-1472, as well as other areas not completely covered in MIL-STD-1472. Some of these areas are twisting lifting, measurement data for tool clearance, and requirements for Personal Protective Equipment. These areas were determined to be the most applicable to KSC

From the comparison analysis there were two recommendations. The short-term recommendation was to add human factors gap requirements into the GS-SRD, and to abide by the MIL-STD-1472. The second longer-term recommendation was to improve the GS-HFRD so it covered all areas of the MIL-STD-1472 and KSC concerns from a set of parent requirements. The first recommendation was chosen because it would best meet the current human factors needs of the GOP. Thus the gap requirements were added into the GS-SRD, and it was decided to archive the draft GS-HFRD. To lessen the burden, these human factors gap requirements do not point to all elements but only to the elements they are most closely associated with, such as Mobile Launcher Element (MLE) and Vehicle Integration Element (VIE).

Benefits from the comparison analysis

Since the GS-HFRD was a set of high-level requirements and MIL-STD-1472 was a large set of lower-level requirements, the comparison analysis led to the development of a matrix showing which MIL-STD-1472 requirements were associated with the GS-HFRD parent requirement. Not only did the work done in the analysis help derive the requirement gaps, it also led to a tool that could help designers develop their design packages for 60% design reviews, and be compliant with the MIL-STD-1472. At the 30% design reviews the key human factors concerns could be identified (but not prioritized) with an expert evaluation checklist process which was based on the GS-HFRD requirements. For the 60% design reviews the associated MIL-STD-1472 requirements could easily be found using the matrix.

Ground human factors as of 2008

At this point the GOP design engineer can rely on the MIL-STD-1472 for all of the human factors requirements, and some gap human factors requirements in the D&S section of the GS-SRD. Furthermore, the design workshops had shown an effective and efficient process for identifying the human factors concerns related to both MIL-STD-1472 and the requirements taken from the GS-HFRD and put into the GS-SRD. Thus at this point in time there are ground processing human factors requirements for designing CxP flight hardware, the flight hardware to ground systems interface, and the ground support systems and ground support equipment leading up to the flight hardware. A recommendation was also accepted to base all future GSE human factors design requirements on the FAA Human Factors Design Standard, which is a better fit with KSC ground operations supporting spacecraft and launch vehicle processing.

Future work in early 2009

As the 60% design reviews for the GSS and GSE designs approach, there are plans to perform human factors assessments, as accomplished in the human factors design workshops, using an evaluation worksheet with human factors experts to identify the ground processing human factors key concerns for each design. The spreadsheet-based matrix tool is planned to be used to link these key concerns with the associated MIL-STD-1472 requirements. For each design, each key area on the worksheet would be considered. If a key area of concern for that design was physical access, then the checklist to MIL-STD-1472 matrix would list all MIL-STD-1472 requirements related to physical access. At that point, design engineering would use judgment to decide which of these requirements adds the most value to improve the design. For example, MIL-STD-1472 has hatch opening sizes, but these standards only outline the minimum opening size and do not account for additions such as moving GSE, tools, or hardware through the opening.

5. ACCOMPLISHMENTS

Flight Hardware Design

From the HSIR flight hardware aspect in relation to ground processing, work is already progressing in many areas. One such area is the motion capture work performed at the United Space Alliance's Human Engineering and Modeling and Performance Lab at KSC to improve design the CEV vehicle. [6] Siceloff Technicians wear motion capture suits to identify ways to improve efficiency of assembly, processing and potential ergonomic risks (Figure-1). Other examples can be found in [4] Dischinger. There is a great benefit by using human factors to improve operations, as the article states, "This is how the techniques for assembling the Orion spacecraft are devised, not by trial-and-error inside a multi-million-dollar capsule, but by computer in a virtual world where no one can drop a life support system on their toe or wrench their back while moving equipment inside."

Figure 1 Technicians hand off a component inside the Orion crew module mock-up.

GS to flight Hardware Interface Requirements Document (IRD)

The IRDs focused the human factors efforts to three key human factors principles, reach, work envelop volume, and visual access. Several designs have been under analysis by using physical simulations or 3D modeling to improve activities that take place at the GS to Ares-I hatch opening, and first stage to upper stage bolt assembly. Other 3D modeling examples of GS to Ares-I interface are shown in Figure-2. And an example of GS to Orion interface is shown in Figure-3.

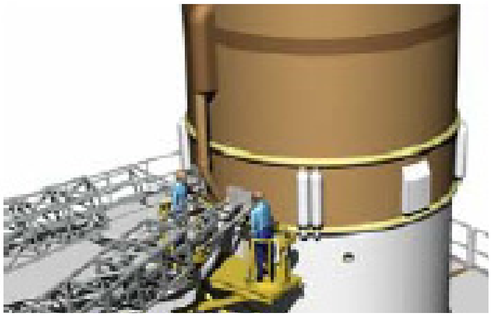

Figure 2 GS to Ares-I

Figure 3 GS to Orion

GS-SRD Requirements

Through the gap analysis of the GS-HFRD and the MIL STD-1472 several areas were found lacking in the MIL-STD-1472. These areas were accounted for by adding requirements into the GS-SRD's, Design and Construction Section. Some of the added gap requirements were to provide better standards for tool clearance and twisting while lifting using the revised National Institute for Occupational Safety and Health (NIOSH) Lifting Equation.

GSE and GSS

As was mentioned previously, human factors workshops were performed on GSE and GSS systems designs. This work has lead to a simple, efficient, and adequate process for proactive evaluation of designs for the 30% design package. Example of the GSE and GSS designs are shown in Figure-4. And other examples can be found in [5] Kanki. This process basically involves one or more experienced human factors personnel using a worksheet to determine the key human factors concerns for each design. For example, for some designs a key concern may be access, but for another design it may be reach or lifting. To ensure all aspects of design are evaluated with respect to the key human factors areas, it is necessary to go through each item in the worksheet.

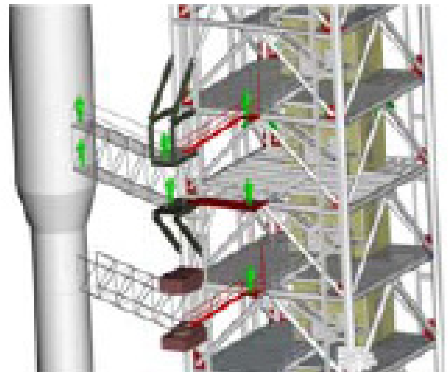

Figure 4 GSE and GSS

GS Level-3 System Engineering Management Plan (SEMP)

The human factors section in the GOP L3 SEMP outlines all areas effecting ground processing, and also explains the that lower levels should do a human factors assessment. It also recommends continued work to develop the KSC-human factors assessment tool for GSE and GSS.

Human Factors Assessment Tool

This work has led to efforts to expand the evaluation process into a tool that can help the designer find the associated standards in MIL-STD-1472. However, the tool is intended to assist a human factors expert, not as a substitute for embedding a human factors expert on the design team.

6. LESSONS

This section is a collection of lessons that have not yet been documented as KSC lessons learned.

- Use available experiences and lessons from prior programs.
- Employ qualified human factors person/s on team from the beginning of the Project.
- Make human factors a proactive part of the design process with well defined requirements that add value to the design.
- Voice the need for human factors where appropriate. Even if it these comments are not accepted, it is still worthwhile since the effort helps to develop a better awareness to human factors.

- In document reviews, look at previous successful human factors program documentation such as FAA, and make comments to promote human factors.
- Try to incorporate human factors proactively, reactively, and everywhere, but use resources for the areas that will get the best results when resources are limited, which is the case when trying to set up human factors into a culture for the first time. Also, build on past successes and combine successes.
- Having requirements at a higher level is important to get acceptance of lower level human factors requirements
- Future NASA programs should consider incorporating all L2 human factors requirements into one document such as the HSIR, e.g., include the ground processing human factors requirements for ground hardware with the ground processing human factors requirements for flight hardware.
- Recommend as early as possible the employment of pilot testing of new processes, but make sure that the efforts of the pilot test will result in added value. When processes are previously in place try to modify them to capture the human factors concerns
- Exercise patience and compromise in gaining acceptance of new requirements.
- From the beginning make sure existing documentation is understood. Work early to improve upon the existing documentation or get buy in from all parties that your document can supersede other existing documentation.
- Because MIL-STD-1472 was used in the past it was hard to adopt a requirements document with less content, even though it would be very difficult to comply with the over 1700 requirements in MIL-STD-1472.
- Human factors engineers should perform the human factors assessments as embedded members of the design teams.
- Do not disregard work that is not accepted when first proposed. To add value to the stakeholders, the work may need adjustment or it may be needed at a later time.

7. FUTURE PLANS

(1) Currently the NASA Administrator is emphasizing the importance of operability. Thus future plans are to leverage the use of human factors to improve design for the human aspect of operability.

(2) Develop and refine the human factors engineering tool and processes to allow efficient and effective means to develop design packages for 30%, 60% and 90% design reviews, and as a tool for final design reviews.

(3) Formally document the human factors assessment process and tool in the L3, L4 and L5 SEMP.

(4) Once the requirements used in the human factors engineering tool become more mature; either incorporate a complete set of the high level (parent type) ground human factors requirements into the NASA-STD-5005 and KSC-DE-512-SM, or incorporate these requirements in the future L3 GS-SRDs, or revise the GS-HFRD to develop a stand alone human factors requirements and assessment process document. Or work to have these ground human factors requirements housed in the L2 HSIR, or future L2 NASA human factors documents.

(5) Once the revised NASA-STD-5005C is accepted by the CxP, the FAA Human Factors Design Standard will be incorporated into the human factors engineering tool.

(6) Make use of human factors principles and analysis during the ground processing activities to prepare flight hardware for the CxP test flights.

(7) Prove the usefulness of human factors so that it will be commonly accepted into the work break down structure at KSC.

(8) Future work for the Human Factors Engineering Tool would be to identify the associated standards and related lessons learned from previous NASA programs and industry, as well as provide proven solutions and analysis methods for the design challenge.

(9) Employ the human factors systems engineering processes and lessons learned from Ares-I to Ares-V.

8. CONCLUSIONS

The original approach for developing the human factors requirements for the GOP was to use the methodology that L2 had done in the HSIR, a small set of key human factors requirements with verification requirements. Through the systems engineering process and experienced leadership in the GOP adjustments were made so the requirements and the implementation of the requirements would be of most benefit to the designers and final design. At the same time we were very fortunate that the NESC promoted the opportunity for the GOP to pilot test the first set of requirements in the human factors design workshops. This not only made the designers aware of the usefulness of human factors, it greatly helped develop the final set of human factors requirements and verification methods that are efficient and effective enough to begin a human factors assessments as early as 30% design reviews.

9. BIOGRAPHY

Damon Stambolian is currently working on a PhD in Industrial Engineering focusing his research on Biomechanics at the University of Miami's Biomechanics Laboratory. He is also currently working in the Constellation Ground Operations Project office at Kennedy Space Center. Prior to working in the Constellation Program he worked in the Space Station Program within the Orbiter Space Plane Project at KSC, and prior to this he worked in the Space Shuttle Program at KSC. In each of these Programs he was involved with process improvements for existing or future ground crew flight processing operations, i.e., assembly, maintenance, and inspection of flight hardware.

List of acknowledgements for others that had influenced the development of the CxP GOP human factors requirements at KSC; Greg Horvath, Jennifer Kunz, Jeff Angermeier, Regina Spellman, Gena Henderson, Jeanne Hawkins, Penny Dippolito, Greg Dippolito, Jeff King, Nathan Gelino, Barbra Kanki, Faith Chandler, Charlie Dischinger Jr., Jessica McLaughlin, Katrine Stelges, Jeff Ewald, and Kim Richards.

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